

# Cuoricino and CUORE

# An overview

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# NSD Staff Monday morning meeting



Berkeley, November 14, 2007

Elena Guardincerri

# Outline

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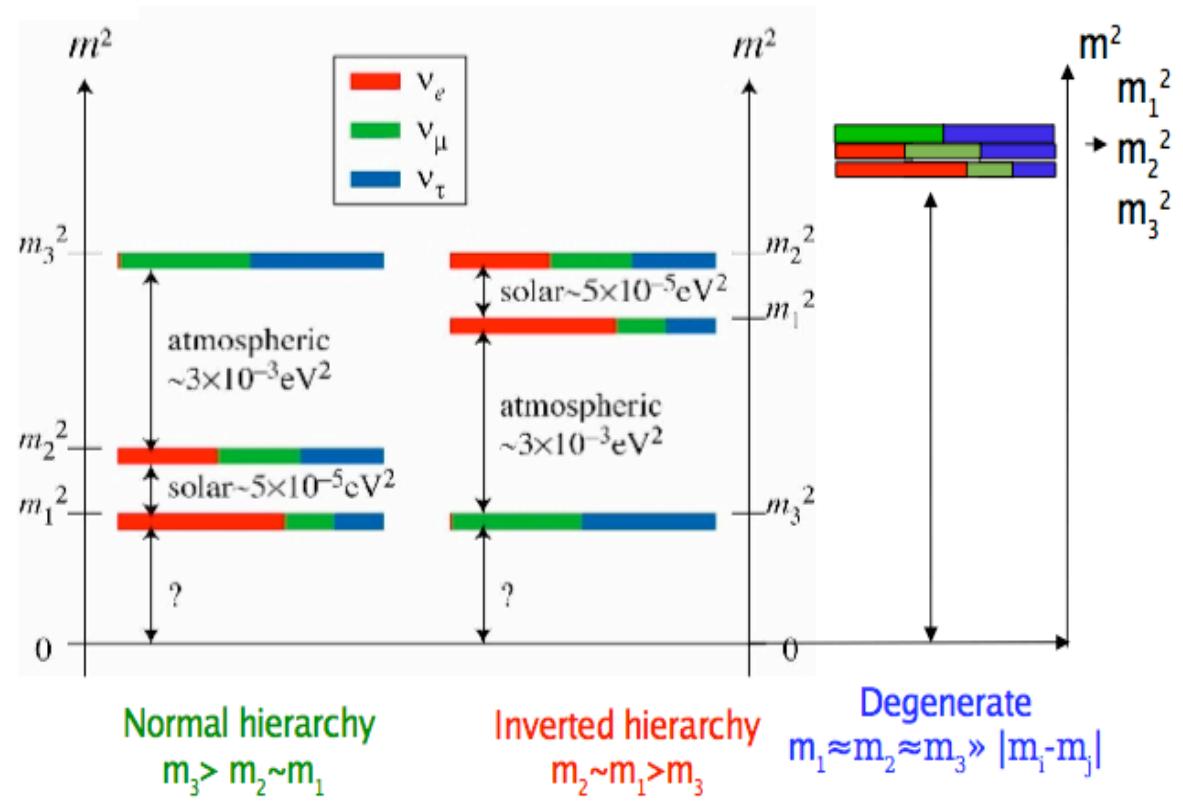
- Status of  $\nu$  Physics and motivations for  $0\nu\beta\beta$  experiments
- Neutrinoless double beta decay ( $0\nu\beta\beta$ ) and the goal of the next generation experiments
- The bolometric approach to  $0\nu\beta\beta$  search
- Results of CUORICINO experiment
- CUORE design and expected performances

# Status of $\nu$ Physics

Neutrino oscillation experiments proved that neutrinos are mixed and massive

## Open questions:

- Absolute mass scale and the hierarchy pattern
- Type of fermion: Dirac or a Majorana?
- $\theta_{13}$  and values of the CP phases



Motivations for  $0\nu\beta\beta$

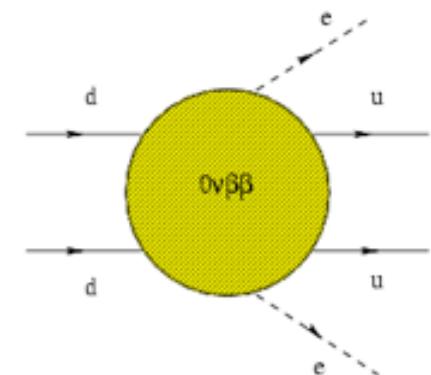
# Neutrinoless double beta decay

## Neutrinoless double beta decay

$$(N, Z) \rightarrow (N - 2, Z + 2) + 2e^-$$

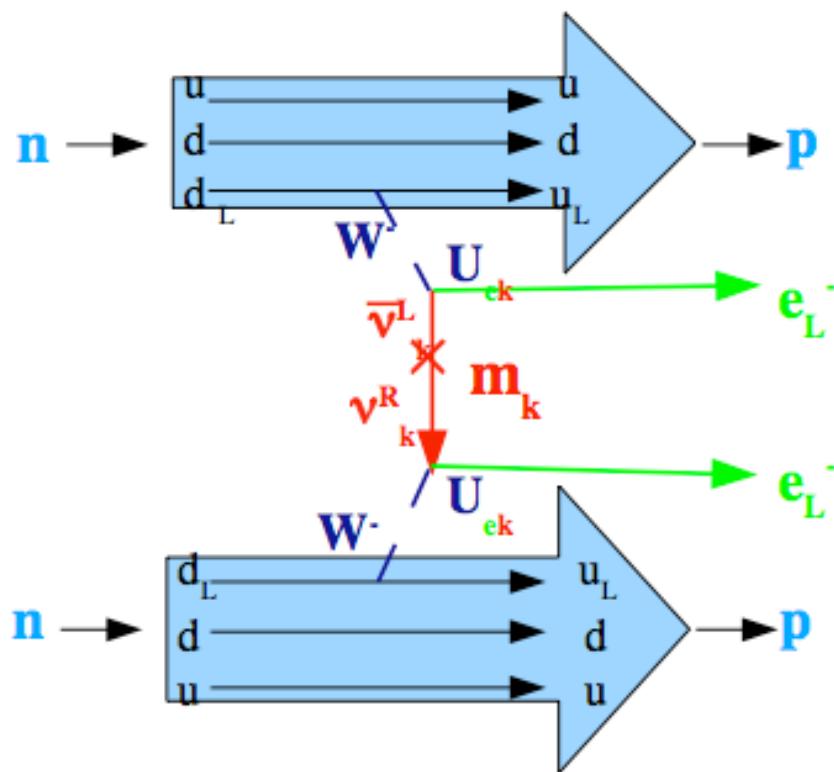
- Not allowed by SM ( $\Delta L = 2$ )
- Claim of observation in  $^{76}\text{Ge}$ :  $\tau = 1.2 \times 10^{25} \text{ y}$
- A part from the claim only lower limits on  $\tau^{1/2}$ 
  - $\tau(^{76}\text{Ge}) > 1.6 \times 10^{25} \text{ y}$
- Possible only if neutrinos are Majorana particles (Schecter, Valle Phys. Rev. D25 2951 1982)

0ν - ββ decay



# $0\nu\beta\beta$ decay and effective mass

In the (standard) hypothesis that the process is mediated by the exchange of a light Majorana  $\nu$  the halflife for  $0\nu\beta\beta$  is:



$$(\tau_{1/2}^{0\nu\beta\beta}) = G(Q, Z) |M_{nucl}|^2 |m_{\beta\beta}|^2$$

Phase space factor,  $\sim Q^5$ , can be computed exactly

Effective neutrino mass

$$m_{\beta\beta} = \left| \sum_k m_{\nu_k} U_{ek}^2 \right|$$

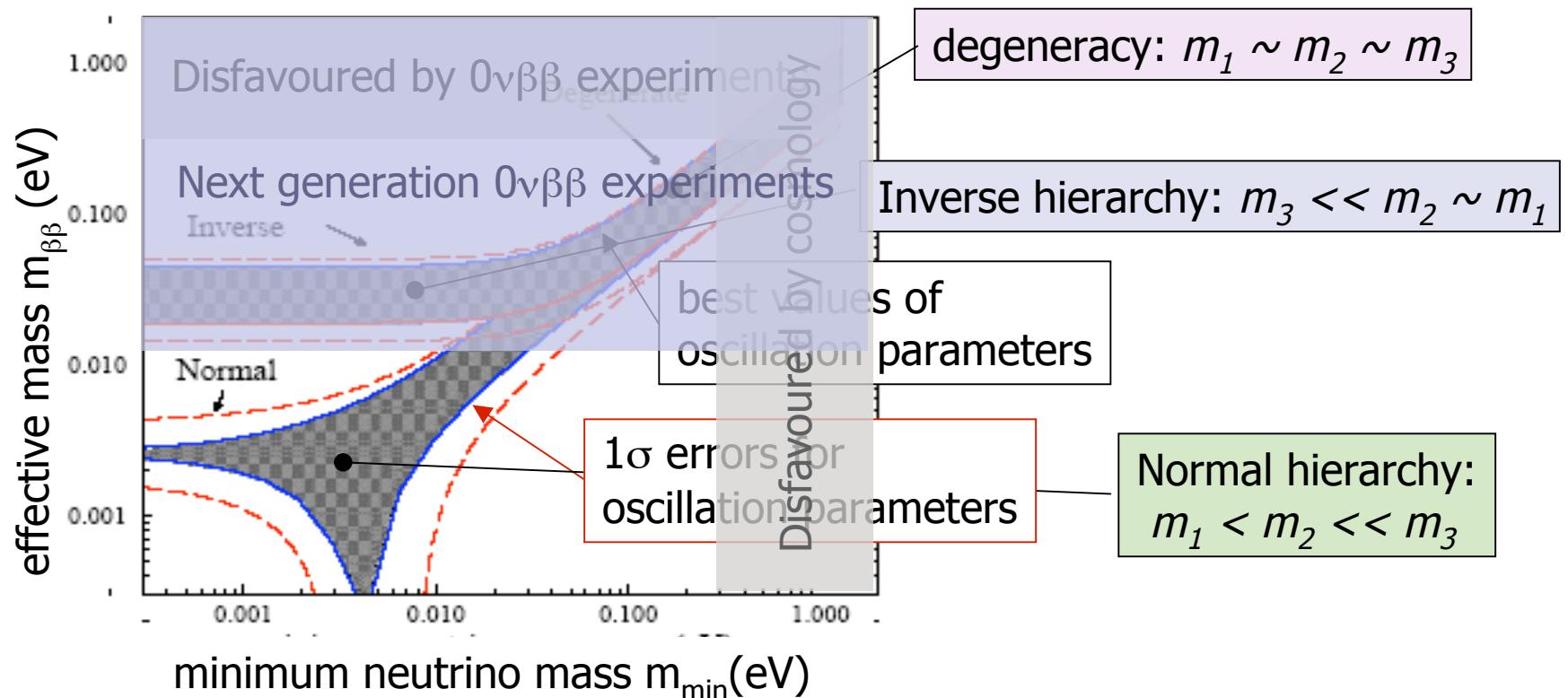
Nuclear matrix element, main source of uncertainty when deriving  $m_{\beta\beta}$  from  $\tau$

From the measurement of  $m_{\beta\beta}$  constraints on the  $\nu$  mass hierarchy can be set

# $0\nu\beta\beta$ and mass hierarchy patterns

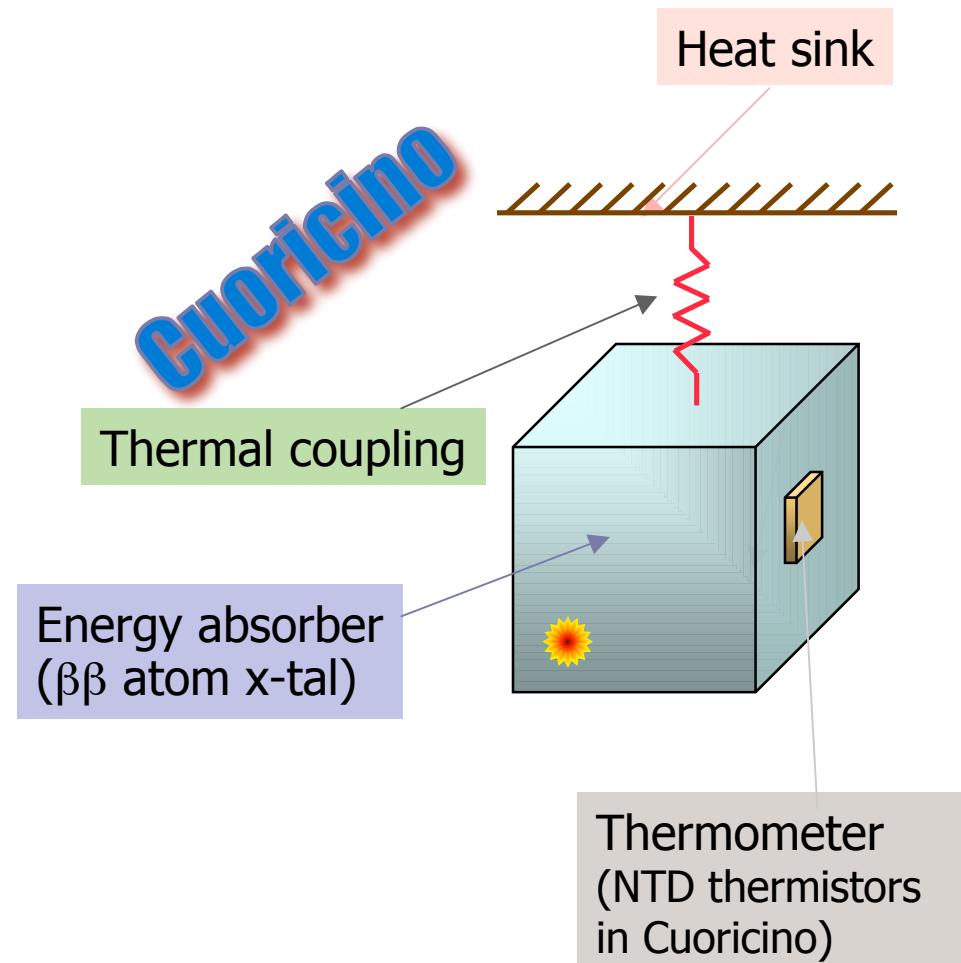
$$m_{\beta\beta} = \left| \sum m_{\nu_k} U_{ek}^2 \right| = \left| \cos^2 \theta_{13} (m_1 \cos^2 \vartheta_{12} + m_2 e^{2i\alpha} \sin^2 \vartheta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13} \right|$$

The results from oscillation experiments can be used to constraint  $m_{\beta\beta}$  and  $m_{min}$ , the mass of the lightest eigenstate (*Strumia-Vissani, hep-ph 0606054*)



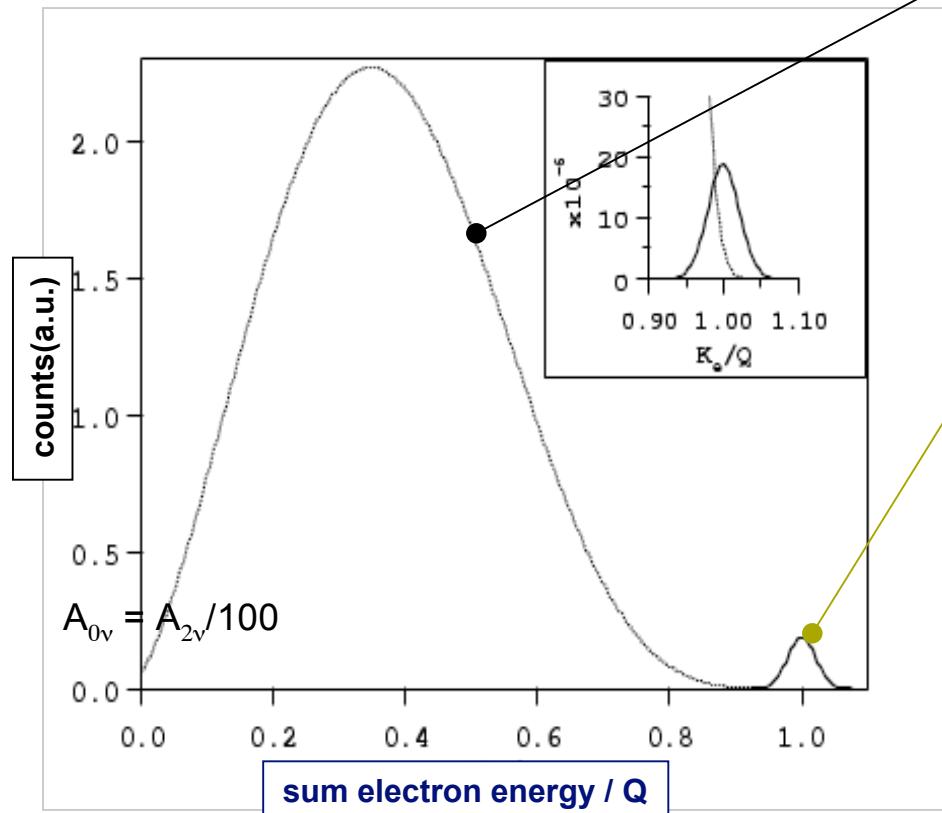
# The bolometric technique

- Principles of operation
  - $\Delta T = E/C$
  - C (heat capacity) low for dielectrics @ low temperatures ( $T \ll 1 \text{ K}$ )  $C \sim T^3$  (Debye)
  - appreciable  $\Delta T$
- CUORE and Cuoricino bolometers are  $^{130}\text{TeO}_2$  x-tals
  - $^{130}\text{Te}$  is one of the nuclei for which  $\beta$  decay is forbidden ( $^{48}\text{Ca}$ ,  $^{76}\text{Ge}$ ,  $^{82}\text{Se}$ ,  $^{96}\text{Zr}$ ,  $^{100}\text{Mo}$ ,  $^{116}\text{Cd}$ ,  $^{128}\text{Te}$ ,  $^{13}\text{Te}$ ,  $^{136}\text{Xe}$ ,  $^{150}\text{Nd}$ )
- NTD Ge thermistors are used as thermometers
- Very good energy resolution
  - See next slides



# Bolometric approach: signature

Measured: sum of electrons kinetic energy



$2\nu\beta\beta$  with maximum at  $E \approx 1/3 Q$ :  
uneliminable background

- $0\nu\beta\beta$  peak at  $Q_{\beta\beta} = M_f - M_i$
- $M_{nucl} \gg m_e$ 
  - nuclear recoil can be neglected
  - peak width due only to detector finite resolution

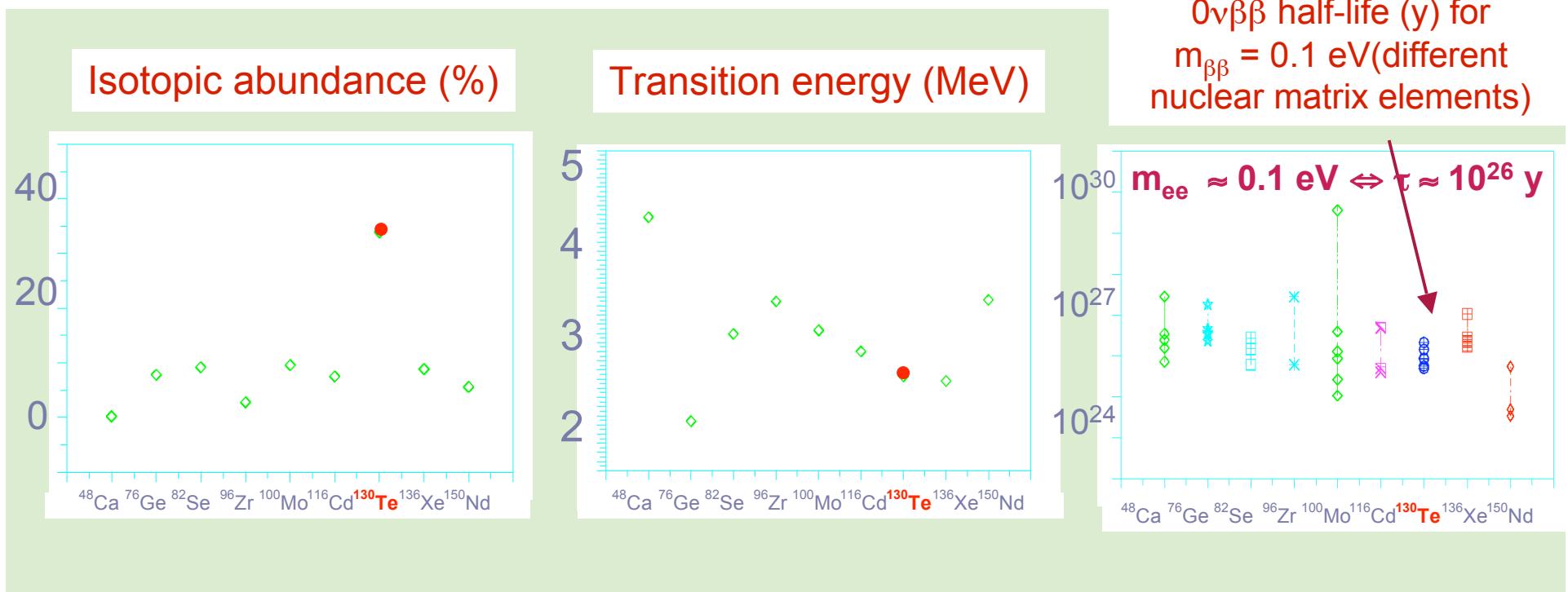
$$\delta = \frac{\Delta E^{FWHM}}{Q_{\beta\beta}} \quad \frac{S}{B} \approx \frac{m_e}{7Q_{\beta\beta}} \delta^6 T_{1/2}^{2\nu} T_{1/2}^{0\nu}$$

6!

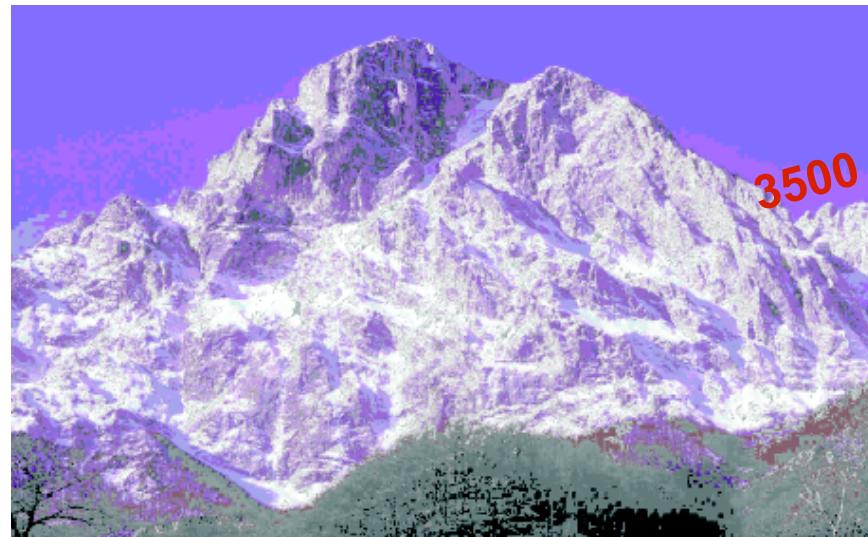
A good energy resolution is fundamental!

# Why $^{130}\text{Te}$ ?

- One of the nuclei for which  $\beta$  decay is forbidden ( $^{48}\text{Ca}$   $^{76}\text{Ge}$   $^{82}\text{Se}$   $^{96}\text{Zr}$   $^{100}\text{Mo}$   $^{116}\text{Cd}$   $^{128}\text{Te}$   $^{130}\text{Te}$   $^{136}\text{Xe}$   $^{150}\text{Nd}$ )
- High transition energy:  $Q_{\beta\beta} = 2530 \pm 1.9 \text{ keV}$ 
  - Low background region (highest natural  $\gamma$  line: 2615 keV  $^{208}\text{Tl}$ )
  - Few counts from  $2\nu\beta\beta$
- High natural isotopic abundance:  $\eta = 33.87 \%$
- Favorable theoretical calculation for nuclear matrix elements



# CUORE at LNGS



3500 m.w.e. shield against  
cosmic rays

Cuoricino (Hall A)

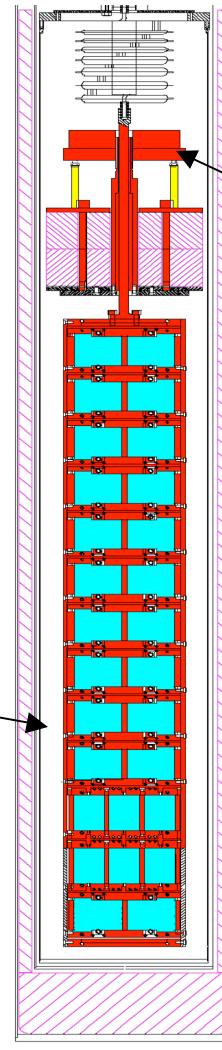
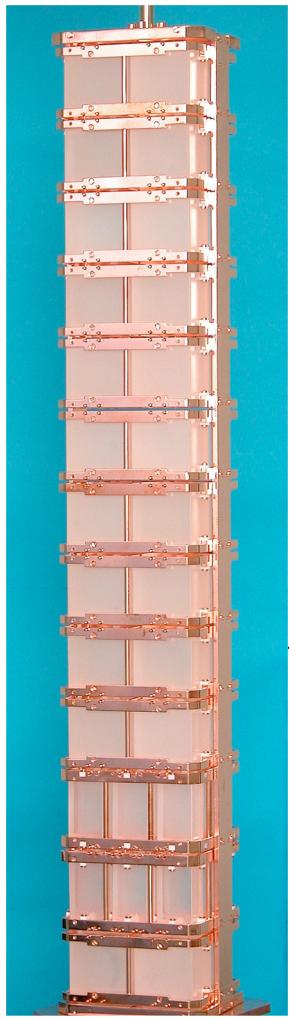
CUORE

CUORE R&D (Hall C)

Underground National Laboratory  
of Gran Sasso  
L'Aquila – ITALY

# The prototype: Cuoricino

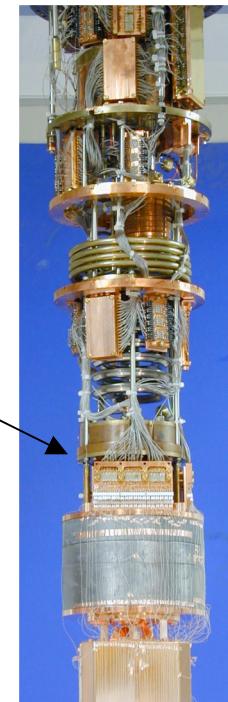
Cuoricino tower: 62  $\text{TeO}_2$  crystals



**mixing chamber**  
 $T \approx 6 \text{ mK}$

Active mass:

- $\text{TeO}_2$  40.7 kg
- $^{130}\text{Te}$  14.1 kg

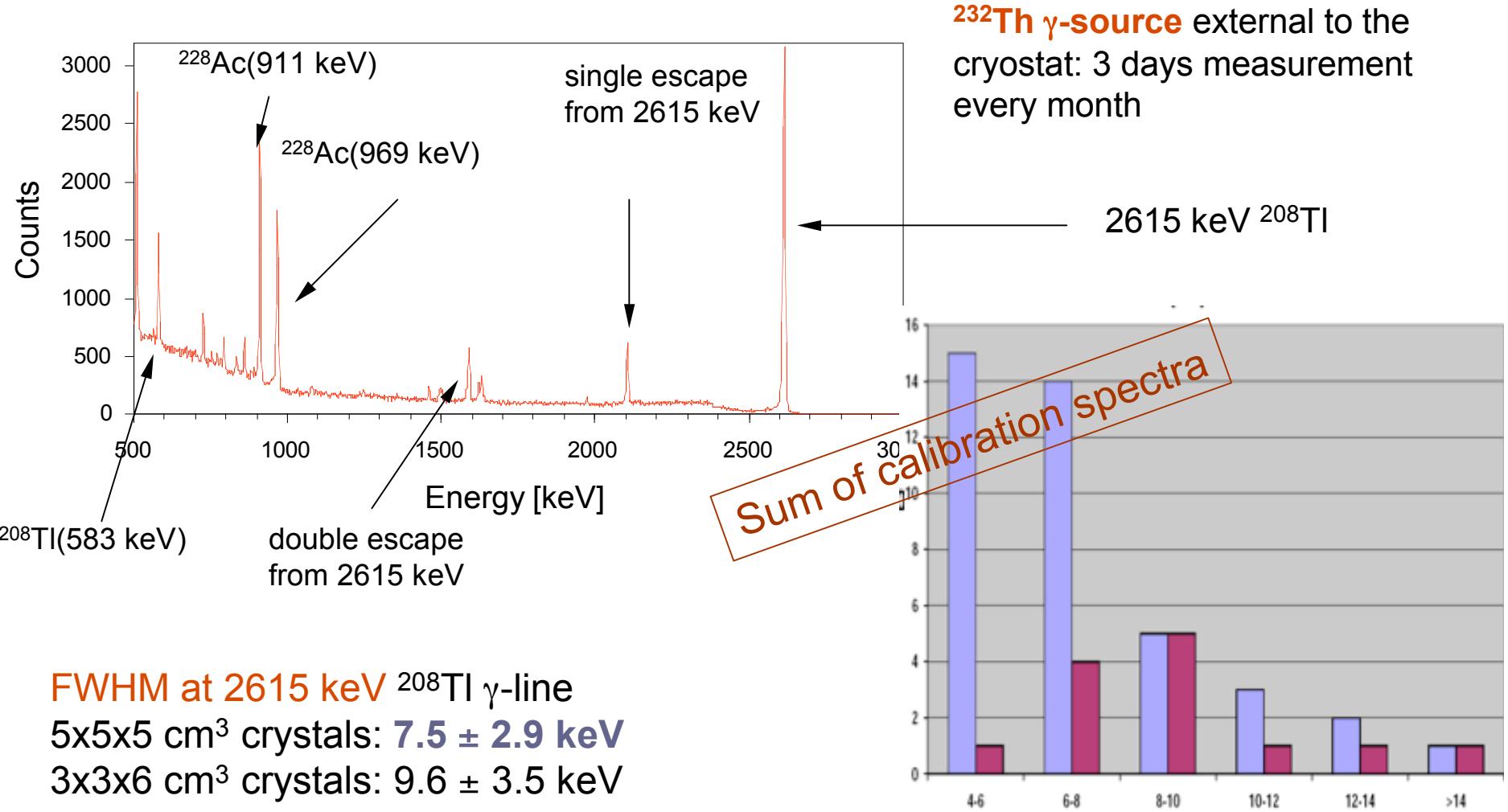


roman Pb shielding (1 cm lateral)

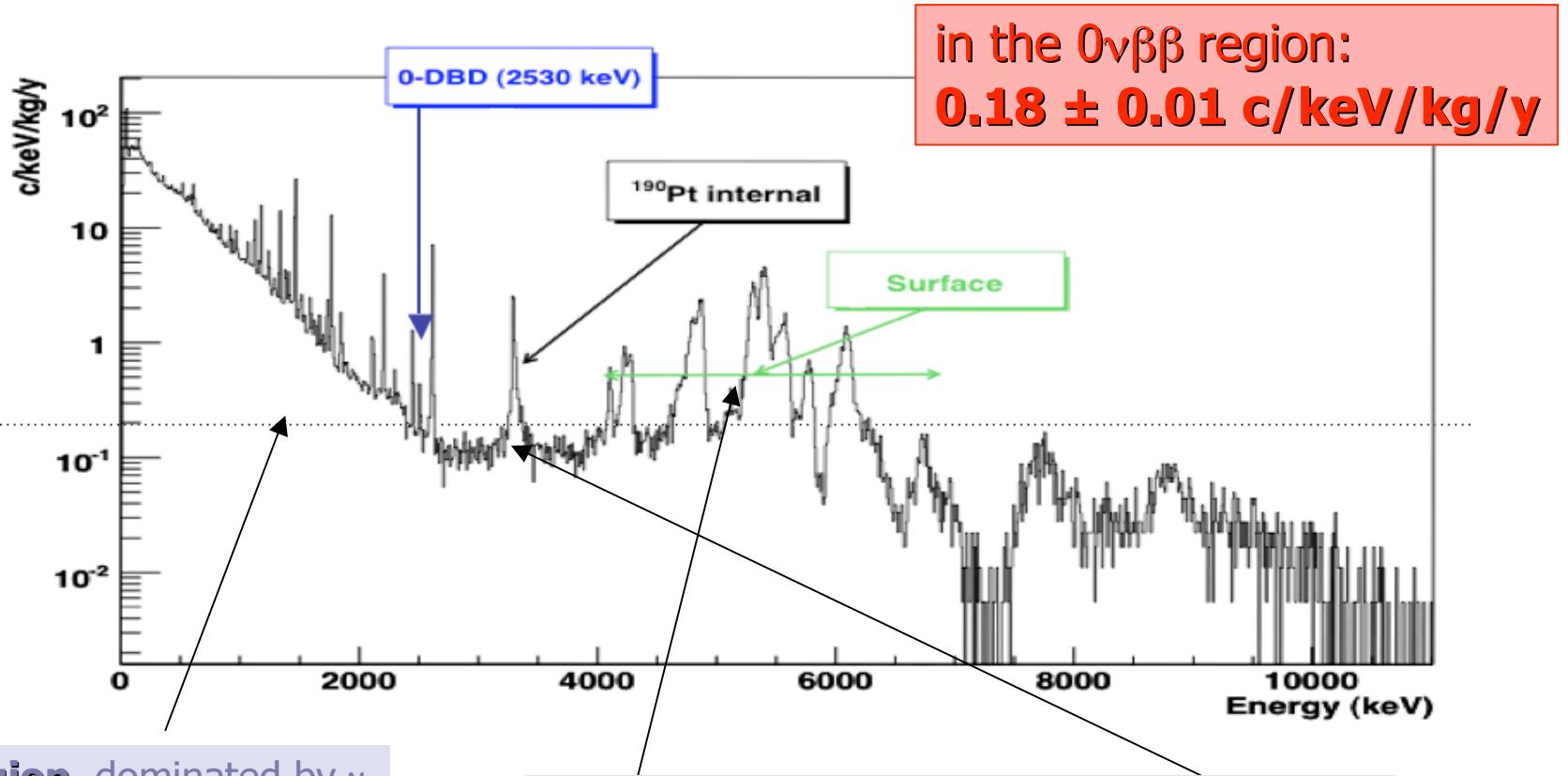
external shields:

- 10 cm Pb + 10 cm low act Pb
- neutron shield: B-polyethylene
- nitrogen flushed anti-radon box
- Faraday cage

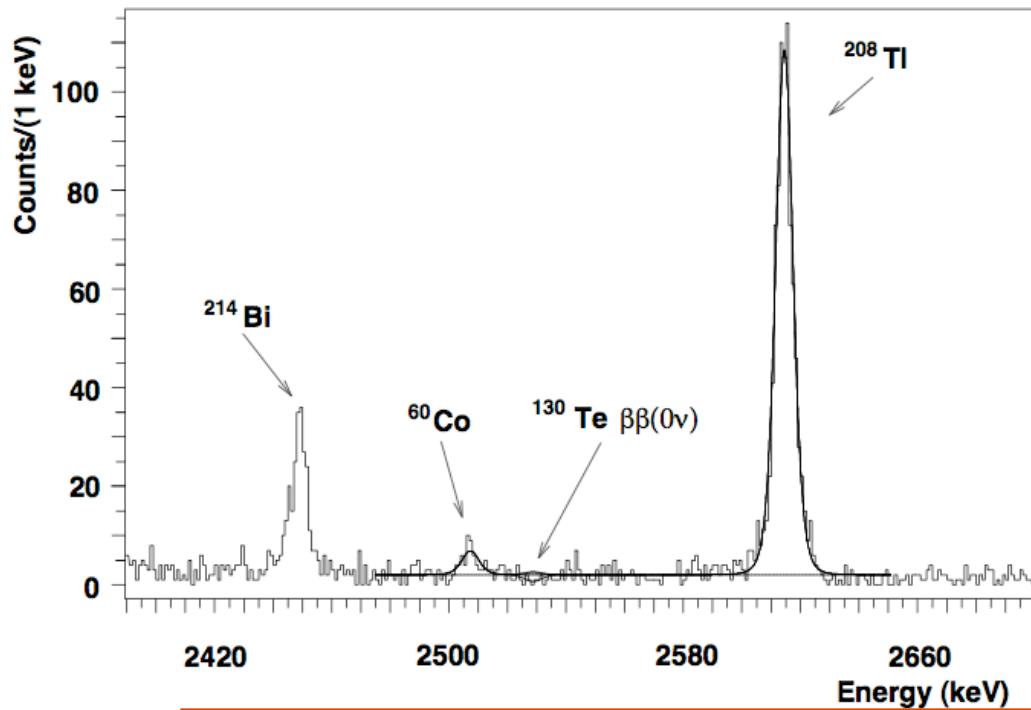
# Cuoricino performances: resolution



# Cuoricino performances: background



# Cuoricino results

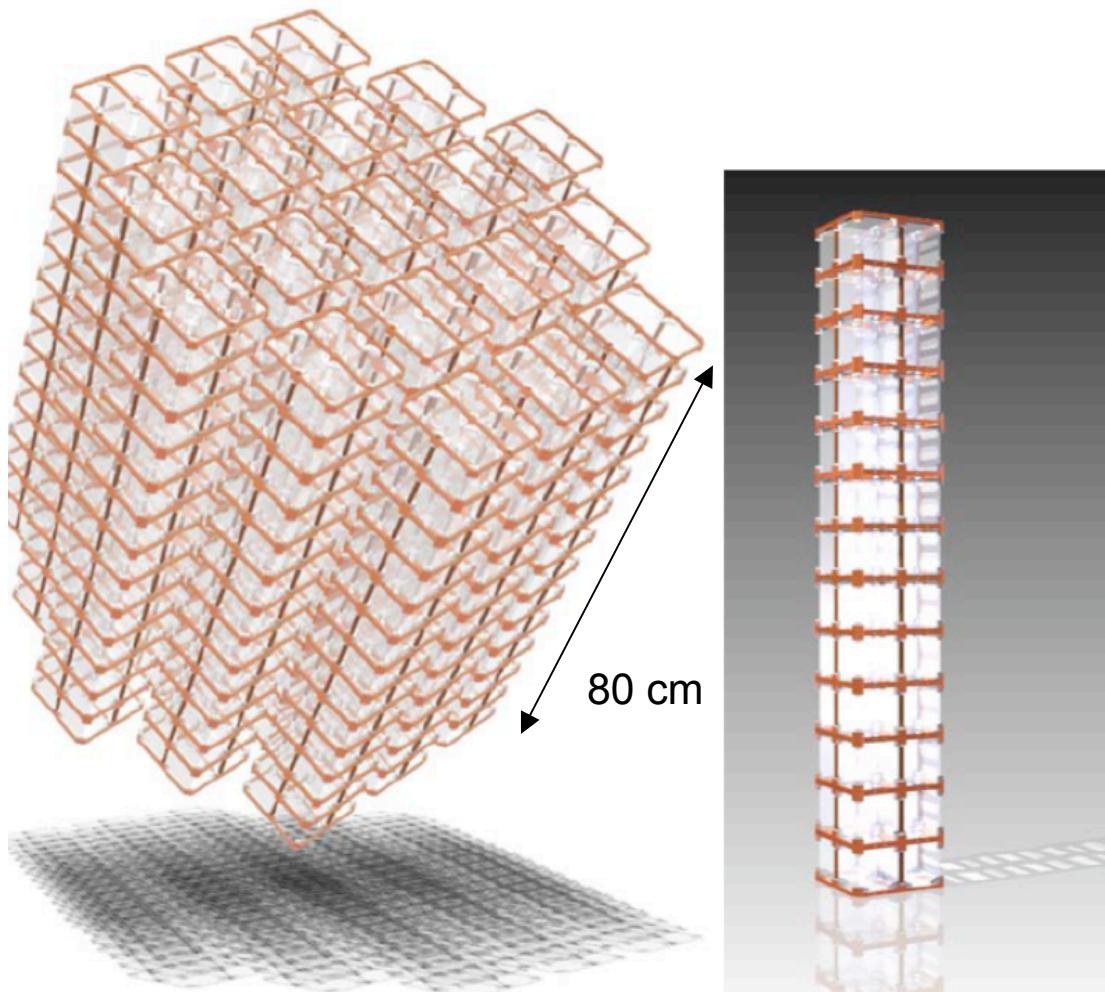


- Total exposure: 11.83 kg  $^{130}\text{Te}\cdot\text{y}$
- Detector efficiency: 86.3%
- Fit in the 2475-2550 keV region
- Flat bkgd + 2505 keV peak
- Peak shape = N gaussians

$$\tau_{1/2}^{0\nu\beta\beta} > 3.0 \cdot 10^{24} \text{ y} \quad @ \text{ 90 \% CL} \quad \Rightarrow m_{\beta\beta} < [0.19 \div 0.68] \text{ eV}$$

Various NME calculations:  
• Rodin et al (2007)  
• Staudt et al (1992)  
• Stoica et al (2001)

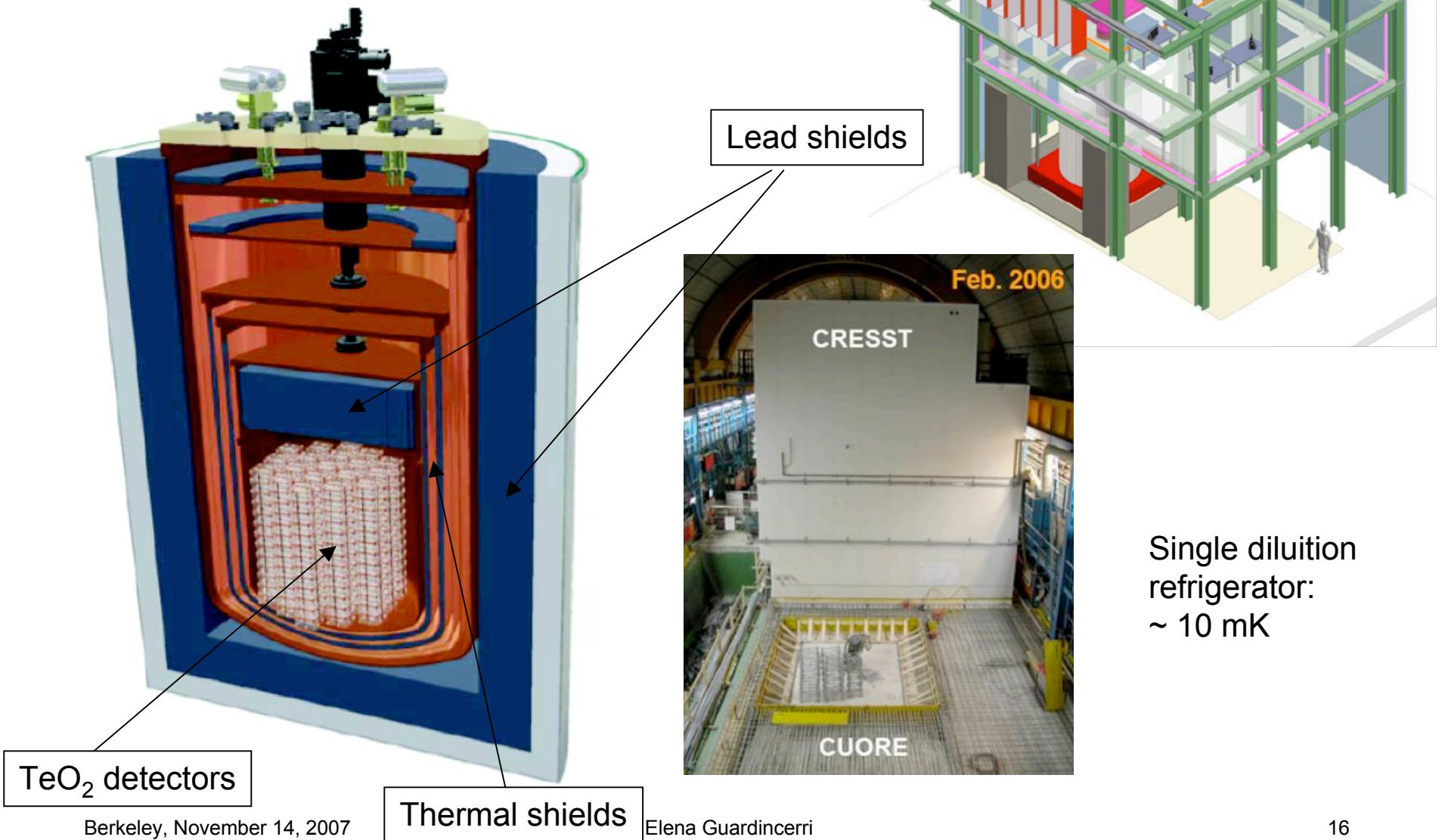
# Cuore setup



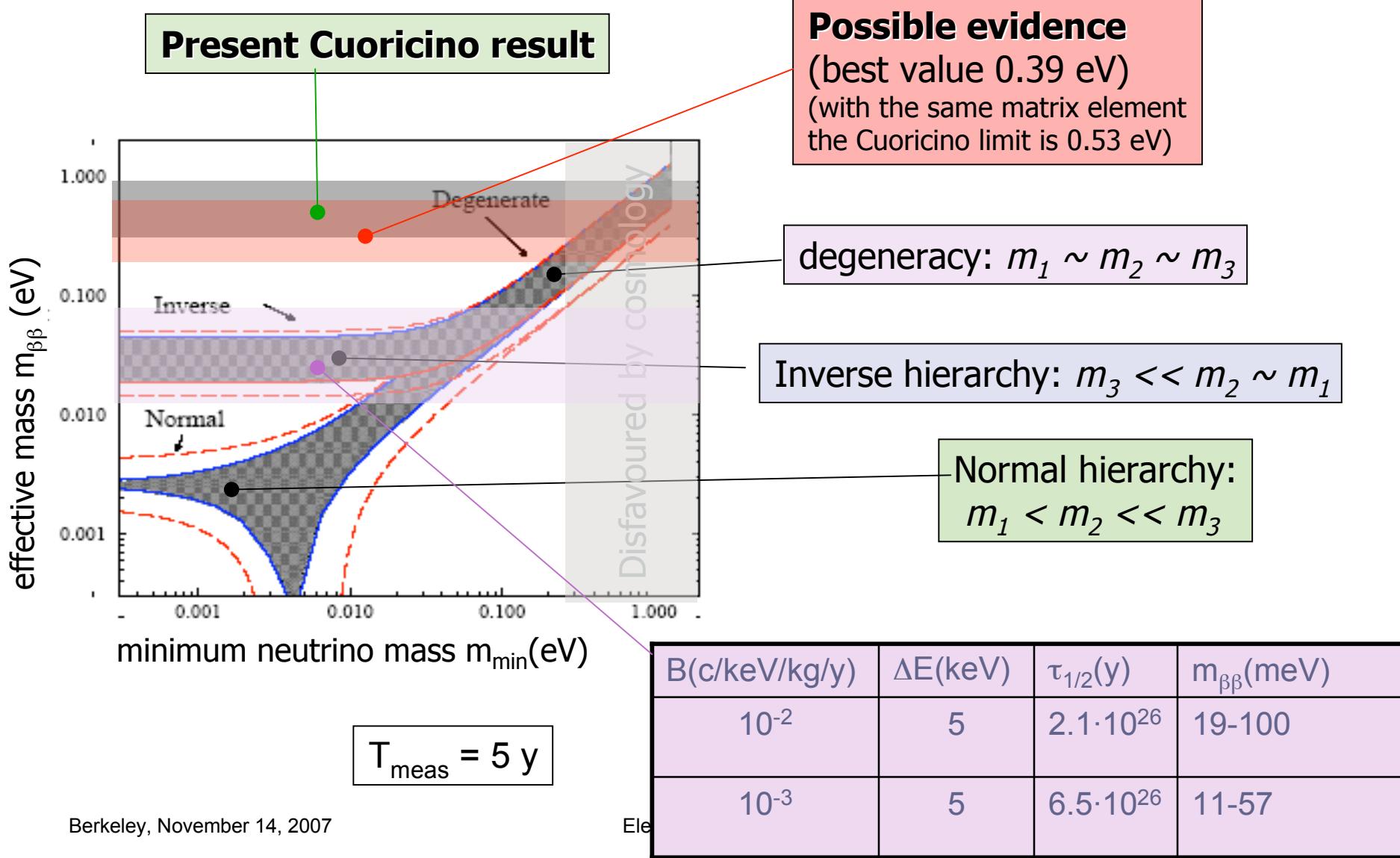
- 988 TeO<sub>2</sub> crystals
- 19 towers of 52 crystals each
- 741 kg TeO<sub>2</sub>
- 203 kg <sup>130</sup>Te

19 times Cuoricino

# Cuore setup



# Cuore expected performances



# Background reduction

- **Cuoricino** bkgd ( $0\nu\beta\beta$ ) = 0.18 c/keV/kg/y (main contributions from contaminations in the construction materials)
  1. Cryostat internal Cu shields (bulk) - 0.072 c/keV/kg/y
  2.  $\text{TeO}_2$  surfaces – 0.018 c/keV/kg/y
  3. Cu surfaces – 0.09 c/keV/kg/y  
negligible contribution from neutrons
- **CUORE** bkgd ( $0\nu\beta\beta$ ) = 0.01 c/keV/kg/y
  - cleaner Cu shields and a thicker internal Pb shield reduces (1) to 0.004 c/keV/kg/y
  - etching and polishing crystals reduces (2) to 0.004 c/keV/kg/y
  - clean or wrap Cu surfaces reduces (3) to 0.034 c/keV/kg/y
  - reduce Cu surface area by ~ 2 reduces (3) to 0.017 c/keV/kg/y  
Total bkgd  $\sim 2.5 \times 10^{-2}$  c/keV/kg/y
- Still a factor 2.5 to go
  - Most experimental efforts are now focused on the reduction of surface impurities

$$S_{n\sigma}^{0\nu} \propto \frac{\eta \epsilon}{A} \sqrt{\frac{MT}{B\Delta E}}$$

# Conclusions

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- Whether neutrinos are **Dirac** or **Majorana** particles is a fundamental question we need to answer
- $0\nu\beta\beta$  might be the only chance to probe the **absolute neutrino mass** scale
- Cuoricino, the most sensitive running  $0\nu\beta\beta$  decay experiment proved the feasibility of CUORE
- CUORE **hut construction** has already started
- **DOE CD-I approval in September 2007**
- Intense R&D activity to **reduce the background** and **optimize the construction**
- **Data taking** is scheduled to start in **2011**

# DBD background contribution for CUORE

	DBD rate [c/keV/kg/y] $\times 10^{-3}$
TeO <sub>2</sub> crystal - bulk	0.7
TeO <sub>2</sub> crystal - surface	5
Detectors mounting structure - bulk	0.6
Detectors mounting structure - surface	35
Internal Pb shield	2.0
Cryostat (Superinsulation + Thermal shields)	1.0
External 30 cm thick Pb shield	0.3
External neutron shield	0.1
Environmental gammas	1.5e-2
Environmental neutrons	0.1
Environmental muons	0.1
TOTAL	44.92

Obtained using **FLUKA + GEANT4**

Assumptions:

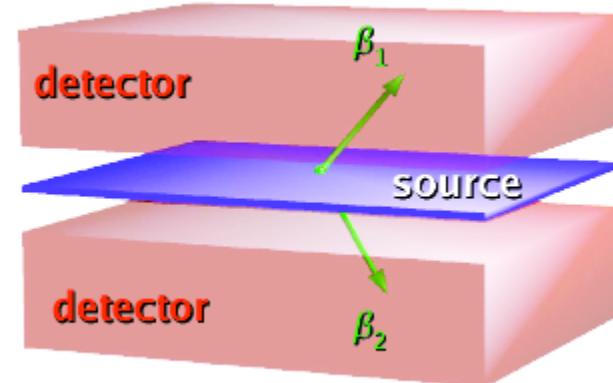
- **Contaminations** in the detector materials = the measured values
- Total **exposure** of the crystals to CR < 12 months
- **Muon** flux in LNGS measured by the MACRO experiment (*M. Cribier et al. (Gallex Col.), Astron. Part. Phys. 6, 129 1997*)
- External **neutron** flux in LNGS:
  - Measured fluxes in LNGS  $\Phi = (3.2 \pm 0.2) \cdot 10^{-8} \mu/\text{cm}^2 \cdot \text{s}$
  - *Mei, Hime Phys. Rev. D73:053004, 2006*
  - Wulandari et al.*hep-ex/0401032*
  - Worst case scenario always chosen

# $0\nu\beta\beta$ : experimental techniques

Allowed only for some **even-even nuclei** for which single beta decay is energetically forbibben

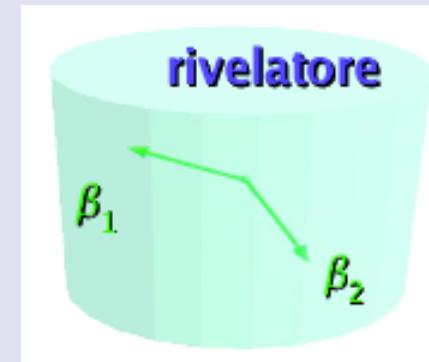
- **source ≠ detector**

- source in thin foils
- electron traces analyzed by means of TPCs, scintillator...
  - **background reduction** by topological analysis
  - angular correlations
  - every possible isotope in a solid phase
  - **only little quantities** of material
  - **low efficiency**
  - **low energy resolution**

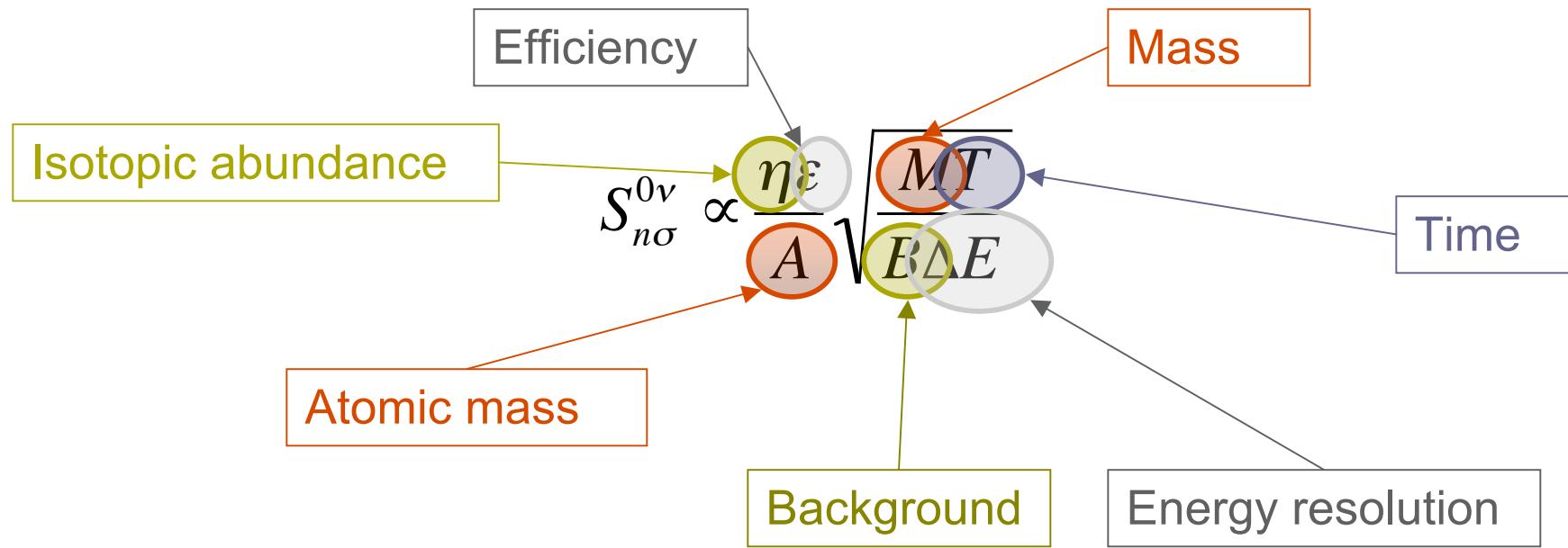


- **source = detector**

- the detector measures the **sum energy**  $E = E_1 + E_2$
- scintillators, **bolometers**, gas chambers, semiconductors
  - big **masses**
  - high **efficiencies**
  - many isotopes
  - depending on the technique:
    - high **energy resolution** (bolometers, semiconductors)
    - certain topological analysis (Xe, TPC, semiconductors)



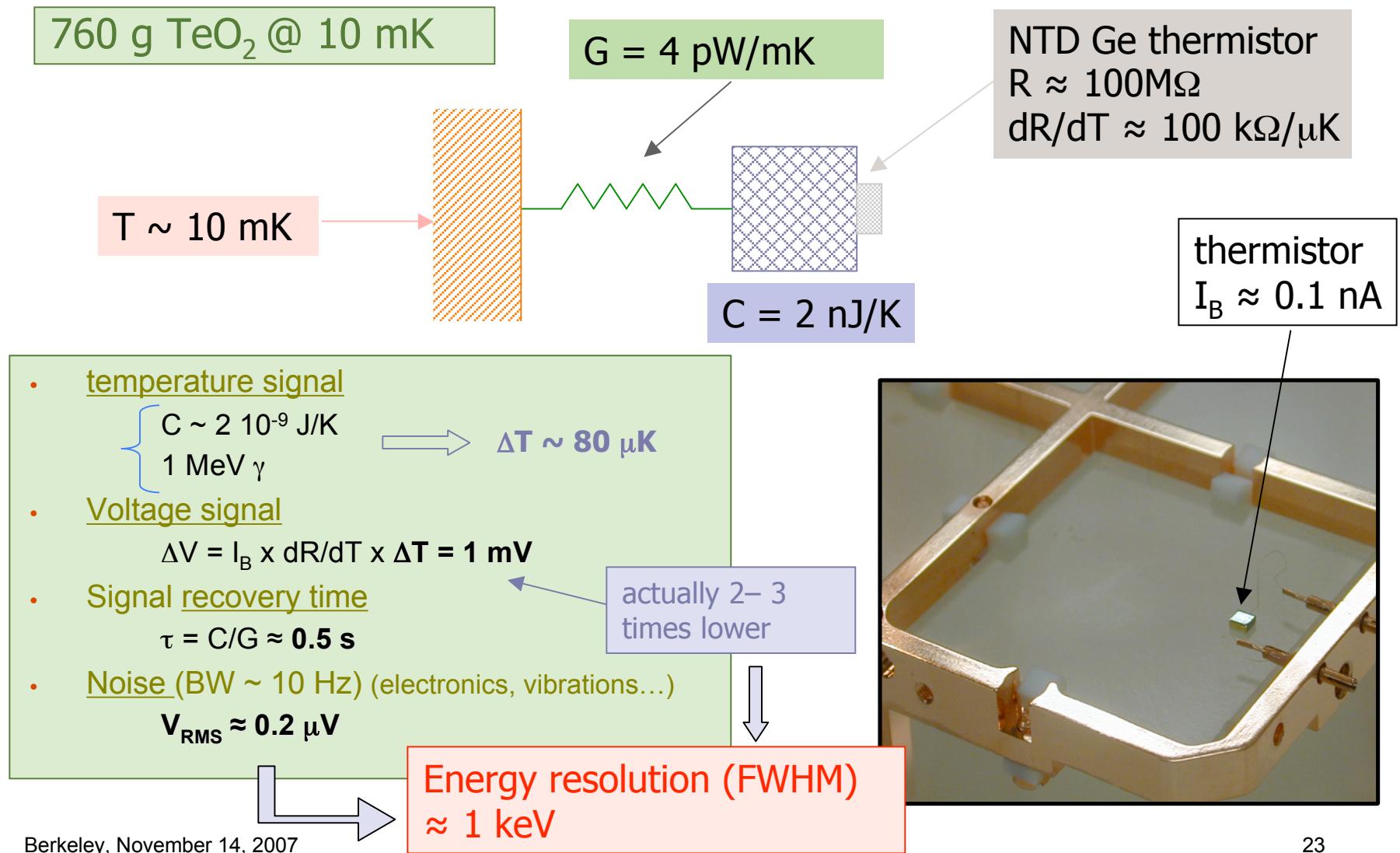
# Sensitivity of a $0\nu\beta\beta$ experiment



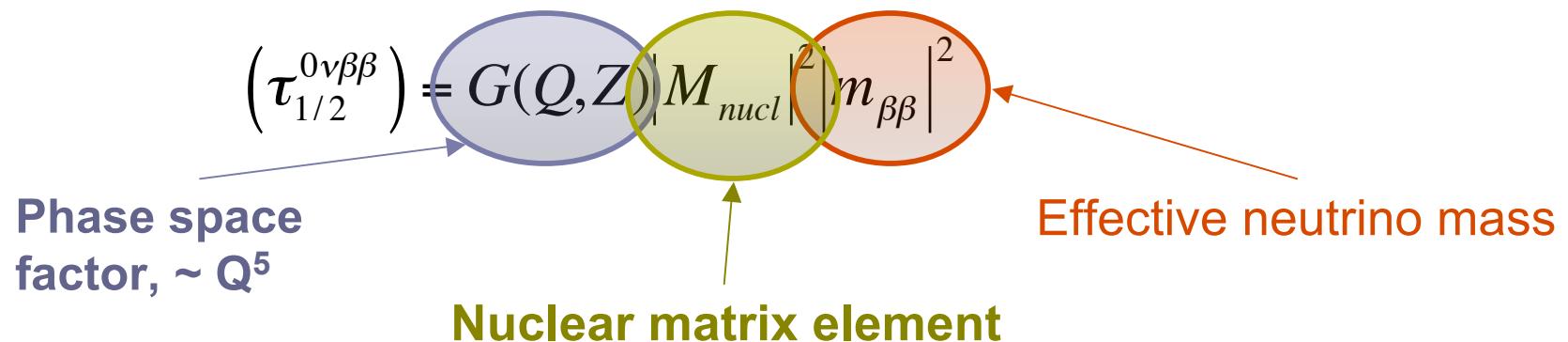
**Sensitivity:** half life corresponding to the minimal number of detectable events above the background, for a given C.L.

With the calorimetric approach, pursued either by  $^{76}\text{Ge}$  diodes or by bolometers highest sensitivities have been achieved

# CUORE and Cuoricino bolometers

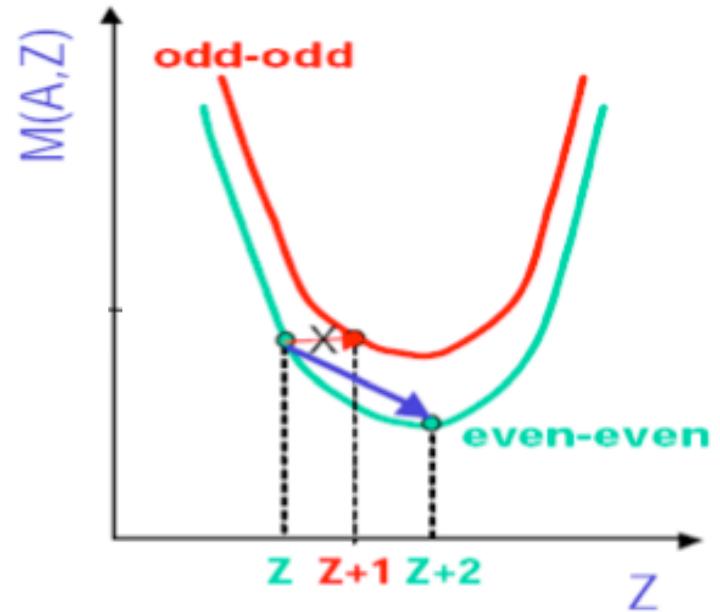


# The choice of the material



The candidate isotope shall...

- have a large  $Q_{\beta\beta}$ 
  - Because the rate is proportional to  $Q^5$
  - Because the natural  $\gamma$  lines end around 2.6 MeV ( $^{208}\text{Tl}$  from  $^{232}\text{Th}$ )
- have large **matrix element**
- be a  $(A, Z)$  even-even nucleus:  $\beta$  decay forbidden
- $^{48}\text{Ca}$   $^{76}\text{Ge}$   $^{82}\text{Se}$   $^{96}\text{Zr}$   $^{100}\text{Mo}$   $^{116}\text{Cd}$   $^{128}\text{Te}$   $^{130}\text{Te}$   $^{136}\text{Xe}$   
 $^{150}\text{Nd}$
- have large **isotopic abundance** (see the next slide)



# $0\nu\beta\beta$ : the background

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- Internal to the source
  - primordial ( $^{238}\text{U}$ ,  $^{40}\text{K}$ ,  $^{232}\text{Th}$ )
  - cosmogenic radioactivity
  - $\beta\beta 2\nu$ : the tail
    - importance of resolution
- External to the source
  - primordial radioactivity in **nearby materials**
  - **Neutrons**
  - **cosmic rays**
- The background is detector specific

## Solutions

- Underground laboratories/**shielding**
- **Materials selection** and purification
- short exposure to cosmic rays
- Choice of **high  $Q_{\beta\beta}$**  isotopes
- Signal treatment
- Other experiments experience

# The prototype: Cuoricino

